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Design of Boat Powered Photovoltaic Systems[1]

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Abstract—The solar energy has high potential applications in Indonesia since the country is located close to the equatorial region that makes the sun is almost bright along the day. In this paper, the boat power photovoltaic system is proposed. Such design may promote new innovations technically and economically in water transportation system since the country demography is almost 75% surrounded by water. The electricity energy is harvested from the sun through the PV panel then stored in the battery by solar charge control mechanism in order to rotate the prime mover of the boat by means the DC motor. The shaft of the DC motor is directly connected to the boat propeller and the speed motor is regulated by the pulse width modulation (PWM) technique generated from the AVR microcontroller ATmega16. The final design is obtained that for the boat with the total weight of 531.1758 kg, it may operate for 1.26 hours with the knot speed of 3.11 when 2 PV panels of 50 W, 2 DC motor of 0.3 kW and battery of 100 A h capacity are used with the overall efficiency performance not less than 87.4%.

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Countries which are located in the equator region are blessed with high potential of solar energy utilization. It is due to the small change of incident angle of sunlight direction that makes the irradiance level can be constantly maintained at high level for years. According to the NASA measurement in Indonesia, the intensity of sunlight reaching the surface is about 5.5 kW h/m^2 per a day. It means high power output of photovoltaic system can be harvested for wide area of installation systems. Sunlight intensity arriving on PV module surface is fluctuated and difficult to be accurately predicted. The weather information is very useful to estimate the irradiance condition in the following days. According to meteorological agency, the duration of sunny condition in Makassar, Indonesia (05°04′ S, 199°33′ E), where the experiment is conducted is average about 7 h during July 2013. It constitutes about 88% of the length duration of effective irradiance during a day.

Indonesia is one of the countries with the wide marine environment. It is archipelagic country consisted of more than 17000 islands and surrounded by deep ocean basins and shallow sea. Our solution is to promote the renewable energy source by means the solar energy to power the boat. They can do battery charging during a day and using the stored energy for fishing during night time. Our boat power photovoltaic system design may encourage the community to change the perspective in terms of using sun energy for sea activities, so it ends up good demonstration and dissemination in the boat design improvement. This effort is supporting the implementation strategy of photovoltaic system utilization in Indonesia, especially for solar boat system [1].

In the world scale, the boat power PV system has been designed since 1991 in Germany. The project is for research vessel called the solar boat “Korona”. In the initial stage, both mechanical and electrical parts were the main consideration according to hydrodynamic behavior. The water vessel is about 1.4 tons in weight powered by 2.2 kW of induction motor and it can reach the maximum speed of 12 km/h with sufficient power reserve under bad weather condition and offering the efficiency up to 62% [2]. There was significant improvement up to 21% in three-phase induction motor performance within the partial load region using vector oriented control. Nevertheless, the problems of solar modules and the reliability of the data acquisition unit still appeared due to partial load energy consumption [3]. These days, the researcher started thinking the orientation of solar energy utilization in static applications to the dynamic problems environment by means the transportation systems. Reduction in fossil fuel energy consumption and its dependency are the main reason taken into account for the economic and environmental benefits [4].

Nowadays, the harvesting energy method from the Sun to power the boat is the main attention since it relates to the conversion efficiency and duration utilization of energy. Therefore, the maximum tracking control is very important to be discussed for dynamic motion of the boats since the irradiance might change rapidly [5]. To increase the efficiency and reliability performance of marine vessels powered PV system, the cogeneration between diesel engine and PV system is

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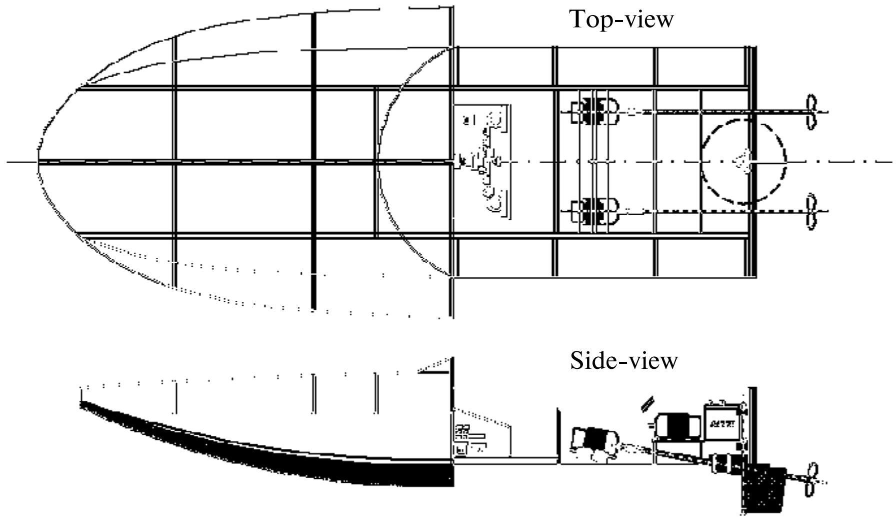

Fig. 1. Boat design overview.

proposed in Geoje Island, South Korea [6]. It is a prototype green ship consisted photovoltaic system, diesel engine, battery energy storage, hybrid control system and a stand-alone grid-connected inverter. The experimental results are confirmed with environmental, economic and sensitivity analysis. In other perspectives, the cost-benefit analysis is taken into account such as reduction carbon gas emission, payback investment and the dependency system on the energy storage media [7]. A good example for the prospect of seaborne transportation system facility utilizing renewable energy is in Taiwan [8]. It is survey base approach about the public willingness of using renewable energy including ship power in maritime industry.

The latest development of marine vessel powered photovoltaic system is focused on the power generation and energy storage systems. These two problems are still the main challenges to be solved in solar power autonomous underwater vehicle [9]. The maximum power point tracking control and the battery configuration are the solution for the energy restriction to the distance sailing. In terms of PV generation system in boat applications, researchers concentrate on the PV module experiments [10]. Light weight and flexibility of shape as well as endurance are required for successful PV-powered boat design. For these purposes, the variety of PV module based polymer are investigated considering cost, weight reduction, strength, UV stability and high transmittance. All developments may disembogue the first solar-powered boat to sail around the world called Tûranor PlanetSolar composite catamaran [11]. The solar energy is stored in a lithium ion battery to power an electric motor. The weight optimization of solar panels, battery and motor is considered to design the boat as light and as robust as possible. In comparison, our proposed boat power PV system design is still small in size and capacity, but there is the significant improvement in the boat speed control design and end up with balancing power flow and high efficiency performance. The design gives a very good chance to promote solar energy utilization to community in our country as well as good media education for students in our campus.

The proposed design is divided into two main components, i.e mechanical design of boat and prime mover design by means the electrical systems. In this research however, the mechanical boat design is not the main consideration but the overview of the boat with front over hang (FOH) type and several technical specifications to calculate the weight of the boat are shown in Fig. 1 and Table 1, respectively.

Meanwhile, the prime mover by means the electrical systems is operated by the mechanism of harvesting energy from the sun through the photovoltaic system, storing the energy into the battery, utilizing the energy from the battery to drive the propeller using DC motor. Therefore, photovoltaic module, charge controller, battery, inverter-rectifier, PWM for speed regulation, DC motor and propeller are needed in this prime mover design. These components are explained as follows.

Photovoltaic Module

In this system, two photovoltaic (PV) modules of multi-crystalline Silicon with 50 Wp each with parallel connection are used according to requirements of charging current to the battery.

These PV panels are mounted at the prow side of the boat in order to reduce the air friction resistance. The increase such resistance will slow down the boat speed. The technical specification of photovoltaic module is shown in Table 2.

The real-time measurement output power of these two PV panels connected in parallel on 7 July 2013

Table 1. Technical specifications for the weight boat calculation

No.	Parts	Area, cm^2	Volume, cm^3	Specific mass, g/cm^3	Weight, g
1	Frame transversal 1	34213.3	68246.6	0.24	16379.184
2	Frame transversal 2	62147.2	124294.2	0.24	29830.608
3	Frame transversal 3	84312.0	168624.0	0.24	40469.76
4	Frame transversal 4	18467.2	36934.4	0.24	8864.256
5	Frame transversal 5	57976.4	115952.8	0.24	27828.672
6	Frame longitudinal center	83880.8	167761.6	0.24	40262.784
7	Frame longitudinal side L	150340.8	300681.6	0.24	72163.584
8	Frame longitudinal side R	150340.8	300681.6	0.24	72163.584
9	Skin 1	62590.7	62590.7	0.24	15021.768
		62590.7	62590.7	0.24	15021.768
10	Skin 2	168488.5	168488.5	0.24	40437.24
11	Skin 3	34400	34400	0.24	8256
		34400	34400	0.24	8256
12	Skin 4	37433.3	37433.3	0.24	8983.992
		37433.3	37433.3	0.24	8983.992
13	Skin 5	48000	48000	0.24	11520
		48000	48000	0.24	11520
14	Skin 6	20858.4	20858.4	0.24	5006.016
		20858.4	20858.4	0.24	5006.016
15	Skin 7	33920	33920	0.24	8140.8
		33920	33920	0.24	8140.8
16	Skin 8	287162.4	287162.4	0.24	68918.976
Total weight, gram					531175.8
Total weight, kg					531.1758

from 8 a.m to 4 p.m under clear sky condition is shown in Table 3. It is obtained that the average output power and input current used for charging battery is 31.73 W and 2.39 A, respectively within the interval of 30 minutes measurement. This simple test is to guarantee that the PV panels are enough to power the prime mover of the boat.

Charge controller utilizes the pulse width modulation (PWM) technology to regulate the battery charging mechanism to supply current from battery to load. The solar panel has usually terminal output voltage between 16 and 21 V. If there is no solar charge controller, the battery is damage due to overcharging and voltage instability because the battery is normally charged in the voltage range of 14–14.7 V. Conventionally, solar charge controller has 2 input terminals connected to the PV panel output and 2 terminal output connected to the battery and other 2 output terminals connected to the load/inverter. The electric current from battery is not allowed to flow back into the

Table 2. Technical specification of photovoltaic module

Parameters	Specifications
Rate maximum power (P_{mp})	50 Wp
Tolerance	±5%
Rate maximum operating voltage (V_{mp})	17.5 V
Rate maximum operating current (I_{mp})	2.9 A
Open circuit voltage (V_{oc})	21.8 V
Short circuit current (I_{sc})	3.3 A
Nominal operating cell temperature (NOCT)	45°C
Air mass function (A.M)	1.5
Irradiance (STC)	1000 W/m^2
Cell temperature (STC)	25°C
Maximum system voltage	715 V
Wind Resistance 2400 Pa	2400 Pa
Weight	5 kg
Dimension	$845 \times 541 \times 30\ mm^3$

Table 3. Real-time output power measurement

Time, hour	Voltage, V		Current, A	Power, W	
	output panel	input battery		output panel	input battery
8.00	13.5	12.86	3.7	49.95	47.582
8.30	13.9	12.96	3.7	51.43	47.952
9.00	15.4	13.00	1.5	23.1	19.5
9.30	13.35	13.18	3.2	42.72	42.176
10.00	13.17	13.13	2.2	28.974	28.886
10.30	13.12	13.04	1.3	17.056	16.952
11.00	12.85	13.03	1.3	16.705	16.939
11.30	12.95	12.88	3.2	41.44	41.216
12.00	13.35	13.26	3.1	41.385	41.106
12.30	13.49	13.43	2.7	36.423	36.261
13.00	13.63	13.56	2.8	38.164	37.968
13.30	13.64	13.71	2.7	36.828	37.017
14.00	13.79	13.70	2.3	31.529	31.51
14.30	13.93	13.74	2.6	36.218	36.218
15.00	13.81	13.63	2.4	33.144	33.0
15.30	15.29	13.18	1.0	15.29	13.18
16.00	13.31	13.29	0.9	11.979	11.961

PV module by diode protection, therefore the DC current only flows from PV panel into the battery.

In practice, the best solar charge controller is the one that can detect the charging condition of the battery. Therefore, it has important function, such as current regulation for battery charging in order to avoid the over-charging and over voltage conditions and current regulation to the load side in order to avoid the over-discharging and over loading conditions and monitoring the battery temperature. In addition, the mechanism of solar charge controller is in the charging mode of the battery focused on the charging time and charging limit condition. Meanwhile, in the discharging mode, the battery supplies current to loads including disconnection when the battery approaches to be empty. The technical specification of solar charge controller is shown in Table 4.

Battery is used to store the energy harvesting from the photovoltaic systems in order to power the boat system in other time during no sunlight. The battery type is the liquid-type where the technical specification is shown in Table 5. In the battery utilization, it is important to know the battery capacity in A h, where the battery capacity of 100 A h is used in this case. The A h meaning in real-practice is not just a simple multiplication between current value and time. It cannot be said that the battery can be 10 A in 10 h operation. There is an *n* factor which is according to the battery construction in the Peukert equation ($I^n t$ = Capacity) that is not equal to 1. If it is assumed $n = 1.2$, for the 10 A application, the battery is fully charged after 6.31 h. In this design, the PV panels produces average 2.39 A for battery charging (Table 3), therefore for the battery of 100 A h, it requires 35.15 h to be fully charging. In fact, the value of *n* may be in the range of 1.05–1.25 A in real applications. During good irradiance condition, the time that needs to reach full charge is faster because the PV panels produce much higher current output.

DC-AC Inverter and AC-DC Rectifier

The DC-AC inverter is used in this design is to convert and boost the output voltage from battery which is 12 V DC to 220 V AC. The voltage transformation is intended to fulfill voltage magnitude of electric motor. In the inverter utilization, several aspects should be considered, for instance the load capacity in Watt should be closed to the rating inverter in order to reach the maximum efficiency operation, the available DC voltage input is 12 or 24 V and the wave form output, either sine-wave or square-wave AC voltage. In this design, the technical specification of DC-AC inverter is shown in Table 6. Because of DC motor utilization, the 220 V AC voltage is converted back to 220 V DC using rectifier based on diode bridge circuit with input current of 10 A.

PWM Technique for Speed Regulation

The pulse width modulation (PWM) is one of the well-known techniques used as the speed regulation for the DC motor including speed rotation, visualization in high speed, forward and reverse modes. The mechanism is very simple which is only based on the

Table 4. Technical specification of solar charge controller

Parameters	Specifications
Ratings	12/24 V (Auto-work)
Ephc-5	12 V or 12/24 V (Auto-work), 5 A
Ephc-10	12 V or 12/24 V (Auto-work), 10 A
Regulation point	14.4 V
Self-consumption	6 mA (maximum)
Low voltage disconnection	11.1 V
Dimension	140×90.5 mm^2
Low voltage reconnection	13.1 V
Terminals	For wire sizes up to 2.5 mm^2
Type of charging	Series PWM 4 stages bulk, boost and float
Weight	250 g
Temperature	−35°C to +55°C
Electronic protections	Short circuit and over current-solar and load
	Reverse polarity-solar, load and battery
	Reverse current at night
	Bank high voltage-load lightning, solar, load and battery
Humidity	100% non-condensing
Enclosure	Ip 22
Case	ABS CE World
Compliance	CE World
Led indications	Green: Charging
	Green-Yellow-Red: Battery levels
	Red: Low voltage warning and disconnection
	All 3 LEDs Blink: To show mistakes

duty cycle regulation. In this respect, the amplitude and frequency of the pulse are kept constant, but the duty cycle is variable depending on the motor speed requirement. If the duty speed ratio increases, the motor will speed up; or vice versa. The maximal motor speed can be reached when the duty ratio is given to 100%. The circuit for the motor speed regulation using PWM technique is shown in Fig. 2.

The pulse width of PWM signal is regulated from *Timer/Counter* pin of AVR microcontroller ATmega16. This is one of the advantages of AVR microcontroller ATmega16 and is available in three type of Timer/counter. In this design, the PWM is the advanced "*timer mode output comparison*". The timer of PWM mode can be modified with counting time opposite with two other Timers. In this design, the Timer starts counting in ascending mode to TOP value, i.e. 0xFF (255) for PWM 8-bit, 0x3FF (1023) for PWM 10-bit and 0x1FF for PWM 9-bit. *Timer/Counter* 0 and *Timer/Counter* 2 only have PWM 8-bit, while *Timer/Counter* 1 has PWM 8-bit, 9-bit and 10-bit. The selection of PWM mode depends on the Timer/counter registers. *Timer/counter* 1 can be used to generate 2 channels of PWM which these two channels are independently each other.

The AVR microcontroller ATmega16 circuit has four ports namely Port A, Port B, Port C, and Port D. These ports are the *bi-directional* path with *internal pull-up selection*. The port A (PA.0 to PA.7) is the bidirectional I/O pins and the ADC input pins, while port B (PB.0 to PB.7) is the bidirectional I/O pins and pins with special function, such as Timer/Counter, analog comparator and SPI. Next, the port C (PC.0 to PC.7) is also the bidirectional I/O pins and pins with special function, such as TWI, analog comparator and oscillator timer. Lastly, port D (PD.0 to PD.7) is the bidirectional I/O pins and pins with special function, such as analog comparator, external interruption and serial communication. The PWM signal port in the AVR

Table 5. Technical specification of battery

Parameters	Specifications
Model	N100
C.C.A	475
Nominal voltage	12 V
Capacity	100 A h (1200 W h)
Dimensions	$407 \times 173 \times 211$ mm^3
Overall	234 hour
Weight without acid approximation	17.3 kg
Electrolyte approximation	6.9 liter
Regular charge current	10.0 A
Layout	1
Terminal	A

Table 6. Technical specification of DC-AC inverter

Parameters	Specifications
Output voltage	220 V
Output frequency	50 ± 2 Hz
Output waveform	Modified Sinewave
Input voltage range	10.0–15.0 Vdc
Fuse	140 A
Low battery alarm (nominal)	10.4–11.0 V
Low battery shutdown point (nominal)	9.7–10.3 V
High battery shutdown point (nominal)	4.5–15.5 V
Battery drain with no ac load (at 12 Vin)	Less than 0.3 A
Peak efficiency	90%
Continuous AC output power	800 W
30 Minutes AC output power	1000 W
Maximum AC output power	2000 W
Dimensions (Length × Width × Height)	108 × 95 × 55 mm^3

microcontroller ATmega16 circuit is located in the port of PD.4, while ports PD.3 and PD.4 provides connections for forward and reverse modes motor runs, respectively.

One of the commons software used is the Codevision AVR C Compiler. The program is written in C AVR program, then it is compiled in order to obtain the hexadecimal file (*.*hex*) extension. The hexa file is then downloaded to the AVR microcontroller ATmega16 for the dc motor speed control utilization.

DC Motor in practice is normally utilized for special purposes such as the applications that need high starting torque within wide speed range. Therefore, in this design, the DC motor is used as the prime mover of the boat, it is the shunt-type DC motor.

DC Motor is available in different sizes; however, the utilization is limited to the application with low speed, low to medium power consumption. Also, the DC motor application is usually found in the clean area environment and less dangerous space due to the potential arc sparking in the motor brushes. For this reason, in this design, the technical specification of DC motor used is type of 73186, Class of 0.3, maximum input voltage of 220 Vdc, maximum input current of 1.8 A, maximum speed of 2000 rpm and output power 0.3 kW.

Propeller is a double-fins design in order to maximize the output power coming from prime mover. The shaft is made of light stainless steel material with the shaft length of 1.5 m including a gear-joint to prime mover and double-bearing construction for the shaft supporting system.

The capacity of battery used in this design is 100 A h (1200 W h). Measurement results to show the correlation between the battery capability, input voltage of DC motor (prime mover) and motor speed (knot) is shown in Table 7. Additionally, the speed conversion is 1 knot is equal to 0.5144 m/s and there are 4 passengers inside the boat during the measurement. It is clearly shown that the increase in motor speed, it needs extra power from the battery, denoted by the increase in battery power supply, battery output current as well as the input voltage to the DC motor. If the depth of discharge (DOD) is considered to 80%, then during the measurement battery capacity is actually

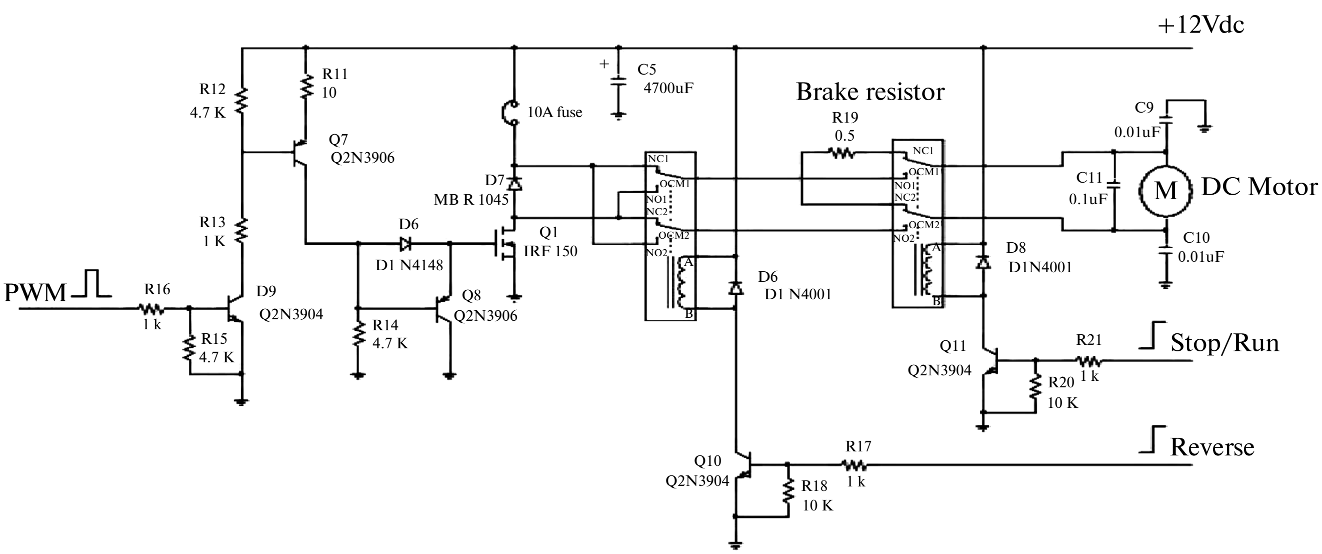

Fig. 2. Mechanism of dc motor speed regulation by PWM using.

effective at 80 A h (960 W h). This effective capacity is used to calculate the time utilization of the battery.

The comparison of time utilization of the battery is shown in Fig. 3. It is clearly shown that when the speed increases, the time utilization is getting shorter due to the rapid drain power from the battery.

According to the experimental test, the Peukert equation based the time utilization of battery is the most suitable approach. If the life-span of the battery increases, the *n* factor increases while the DOD percentage reduces to make the time utilization much shorter than the time values shown in Fig. 4.

In terms of the characteristics of boat speed to the electrical behavior of prime mover by means the DC motor, the measurements of the effective power of DC motor, stator current, DC motor speed and Torque are conducted. The correlation between the boat speed and the effective power is intended to determine the necessity power needs from the battery in order to reach the maximum boat speed. It is very interesting results as shown in Fig. 4 because the maximum boat speed (3.11 knot) is reached as the DC motor operates at its rating capacity (0.6 kW). The result shows that the power flow mechanism between production and absorption is balanced in this design.

It is also important to determine the characteristic of boat speed the electrical behavior of DC motor. The electrical behaviors include the input current and voltage, motor rotation, torque and loading system. The motor loading assumptions in this design includes the propeller friction in the shaft, under water and the depth of the propeller. The measurement results are shown in Fig. 4. Of course, the propeller speed by means the DC motor speed is proportional to the boat speed. The increase in DC motor speed requires the additional input voltage and stator current of the motor. The result is pretty similar under testing characteristic of shunt DC motor. There is typical result when the stator current is reduced to 1.2 A (boat speed of 1.672 knot). This condition is affected from suddenly reduced the loading condition due to the change in propeller depth into the water. In addition, the torque of shunt DC motor which is proportional to speed, it reaches the torque maximum under the maximum speed of the boat.

Table 7. Battery capability to the input voltage and speed motor

Speed, knot	Input voltage DC motor, V	Battery power, W	Battery current, A
1.128	40	199.68	15.6
1.672	60	317.44	24.8
2.333	80	409.6	32
3.11	100	555.52	43.4

Table 8. Input-output power flow

Components	Input Power, W	Output power, W	Efficiency, %
Battery	555.52	409.6	73.7
Inverter	409.6	348.16	85
Rectifier	348.16	313.34	90
PWM controller	313.34	297.67	95
DC Motor (2)	595.34	555.52	93.3

The last point about our design is the power distribution flows through components of battery, inverter, rectifier, PWM controller and DC motor under the maximum speed of the boat. The input-output power flow is tabulated in Table 8 including the efficiency of each component. From this result, it can be summarized that the overall efficiency performance is not less than 87.4%.

The technical information of boat design is provided and the electricity energy provision to power the propeller of the boat including the control system is

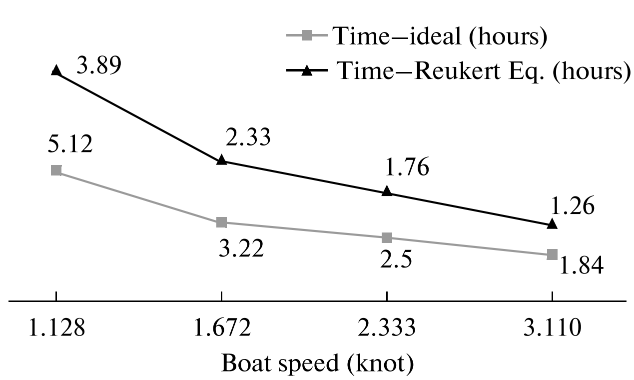

Fig. 3. The battery time utilization.

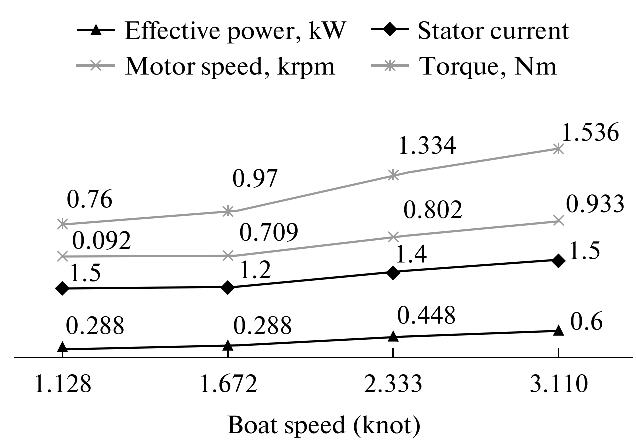

Fig. 4. Characteristic of boat speed to the electrical prime mover.

clearly explained. The electricity energy is harvested from the sun through the PV panel then stored in the battery by solar charge control mechanism in order to rotate the prime mover of the boat by means the DC motor.

The shaft of the DC motor is directly connected to the boat propeller and the speed motor is regulated using the pulse width modulation (PWM) technique generated from the AVR microcontroller ATmega16. After several testing, the final design is obtained that for the boat with the total weight of 531.1758 kg, it may operate for 1.26 hours with the knot speed of 3.11 when 2 PV panels of 50 W, 2 DC motor of 0.3 kW and battery of 100 A h capacity are used with the overall efficiency performance not less than 87.4%.

REFERENCES

1. Dasuki, A.S., Djamin, M., and Lubis, A.Y., *Renew. Energy*, 2001, vol. 22, nos. 1–3, pp. 321–326.
2. Schaffrin, C., Benndorf, S., and Schneider, S., *Clean Safe Energy Forever*, 1990, vol. 1, pp. 359–363.
3. Schaffrin, C., Bystron, K., Glunk, A., and Henke, W., *Proc. Solar World Congr.,* 1992, pp. 479–484.
4. Marsh, G., *Refocus*, 2001, vol. 2, no. 8, pp. 30–32.
5. Shih-Hung, K. and Ru-Min, C., *Solar Energy*, 2012, vol. 86, no. 6, pp. 1750–1760.
6. Kyoung-Jun, L., Shin, D., Dong-Wook, Y., Han-Kyu, C., and Hee-Je, K., *Energy*, 2013, vol. 49, pp. 475–483.
7. Glykas, A., Papaioannou, G., and Perissaki, S., *Ocean Eng.*, 2010, vol. 37, no. 7, pp. 592–602.
8. Hua, J., Yi-Hsuan, W., and Pang-Fu, J., *Renew. Energy*, 2008, vol. 33, no. 5, pp. 1056–1063.
9. Yuli, H., Jiajun, W., and Part, C., *Energy Proc.*, 2012, vol. 16, pp. 2049–2053.
10. Gorter, T. and Reinders, A.H.M.E., *Appl. Energy*, 2012, vol. 92, pp. 286–297.
11. Article in Reinforced Plastics, 2010, vol. 54, no. 3, p. 6.